Simulation Development for Ultra-High Energy Neutrino Experiment

Research Thesis

Presented in partial fulfillment of the requirements for graduation *with research distinction* in Physics in the College of Art and Science of The Ohio State University

by

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CONTENT

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Since the discovery of neutrinos in the last century, scientists have been fascinated about their unique properties that inspire new physics studies. Meanwhile, physicists find it valuable to detect the ultra-high energy neutrinos as cosmic rays in the universe because they contain useful information on the origin of the radiation. Antarctic Impulsive Transient Antenna (ANITA) is one of these experiments looking for the interactions of neutrinos with the ice sheet of Antarctica, whose study is significant for the future researches on astrophysics. These neutrinos, containing energies between 10^{18} to 10^{21} eV, are the only type of particles that can travel billions of light years to Earth at these energies. The experiment adopts a tool built on Monte Carlo simulation to predict the observations before detecting, which further creates a monitor program to test the simulation and visualize the simulated results. My research focuses on developing this monitor program that runs the simulation program and makes analysis plots of the neutrino properties with the simulated data.

INTRODUCTION

Antarctic Impulsive Transient Antenna (ANITA) experiment is designed to study the cosmic rays of ultra-high energy (UHE) neutrinos (<10^{18} eV) by detecting the radio signals generated from their interactions with the ice sheet of Antarctica. We conduct the detection in Antarctica because the looping airflow at the South Pole provides an ideal environment for a balloon experiment. Also, the radio signals are more likely to travel farther with the interaction of the ice than the water or earth. The balloon-borne payload (Figure 1) of this experiment flying around the continent looks for neutrinos at the energy levels from 10^{18} to 10^{21} eV. The detector carries an upper set of antennas and a bottom set of antennas both aimed down 10 degree to face the ice (Figure 2), which sense the radio signals from the interaction between the neutrino and the ice. The total height of the detecting part is 7.5 meter with its largest width of 5 meters at the bottom (Figure 2).

In this experiment, we apply the principle of interferometry to identify the location of interaction. Due to the location difference between the upper and bottom antennas, they will detect the same signal at different times if a radio pulse reaches the balloon. Through mathematically calculating the time and location differences, we are able to find the source of the signal where the interaction has happened. The purpose of studying astro-particles is to explain the origin of these cosmic rays that can lead to the structure and evolution of the universe at highest energies [2]. Neutrinos are able to propagate and survive over long astrophysical distances without interacting with the cosmic microwave background, making them the only type of particles that can reach the Earth unattenuated [4]. As the first NASA observatory for neutrinos, ANITA experiment is expected to obtain useful information on the galaxies emitting the particles for further astrophysical studies.

The major work of my research is developing and improving the simulation of ANITA experiment by visualizing the simulated results. A useful program that my group has built for completing this task runs the simulation and makes histogram plots of the results that we expect to see in the experiment. An initial set of plots were created by Dr. Hoover and Dr. Connolly in 2005 to initially test the workings of Monte Carlo simulation [1]. Thanks to the previous work of Brian Clark, Kaeli Hughes, Khalida Hendrick, and Natalie Keyes on writing the first version of this program.

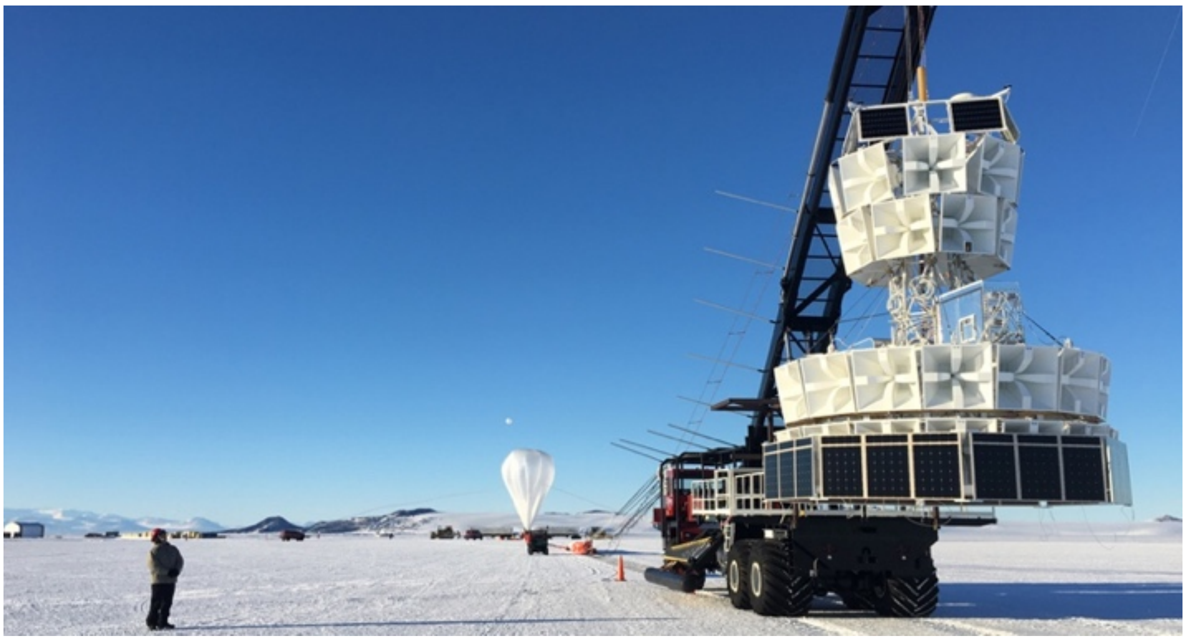

Figure 1. Balloon Payload of ANITA experiment, *Science Magazine*, https://www.sciencemag.org/news/2018/09/oddball-particles-tunneling-through-earth-could-point-new-physics. The picture is shoot by other ANITA collaborators in Antarctica.

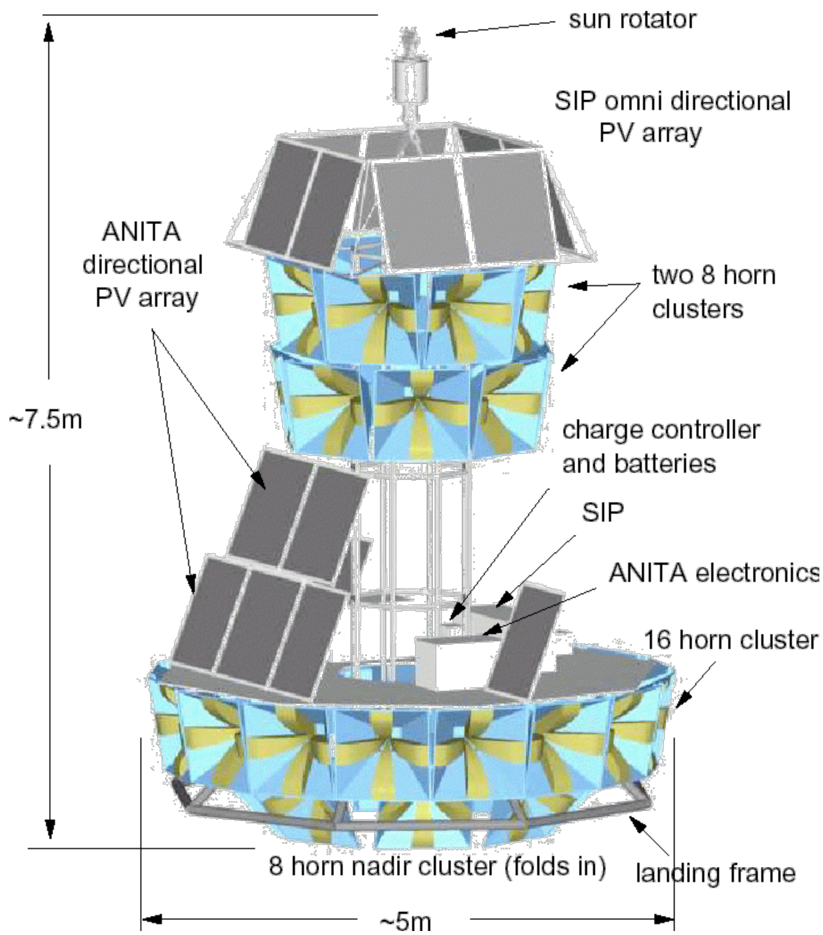

Figure 2. Detector structure with the upper and bottom antennas. The diagram is made by ANITA collaborator and found in OSU ASPIRE presentation in 2019

THEORY

The Askaryan effect reveals that particles traveling faster than the phase velocity of the light in the dielectric generate a shower of charged particles containing a charge anisotropy that emit a cone of coherent radiations in the radio or microwave frequency of electromagnetic wave [5]. It was first postulated by Gurgen Askaryan in 1962 as an extension of the Cherenkov radiation theory, which has been observed in the ice by an experiment in 2007 [5]. ANITA experiment uses Askaryan effect to look for the interaction between the UHE neutrinos and the ice sheet of Antarctica, where the balloon payload detects the signals at radio frequency coming from the ice [3]. Figure 3 gives a good demonstration on how these signals are generated. The photons in the ice travel slower than their speed in the vacuum, while neutrinos can still propagate at the vacuum light speed in the ice. Therefore, the UHE neutrinos move faster than the phase velocity of the light in the ice. The interaction between the neutrinos and the nucleus in the ice results in a Cherenkov cone. The shower of photons with radio frequency are more likely to be refracted by the ice-air surface and later detected by the balloon payload than the photons with shorter wavelength.

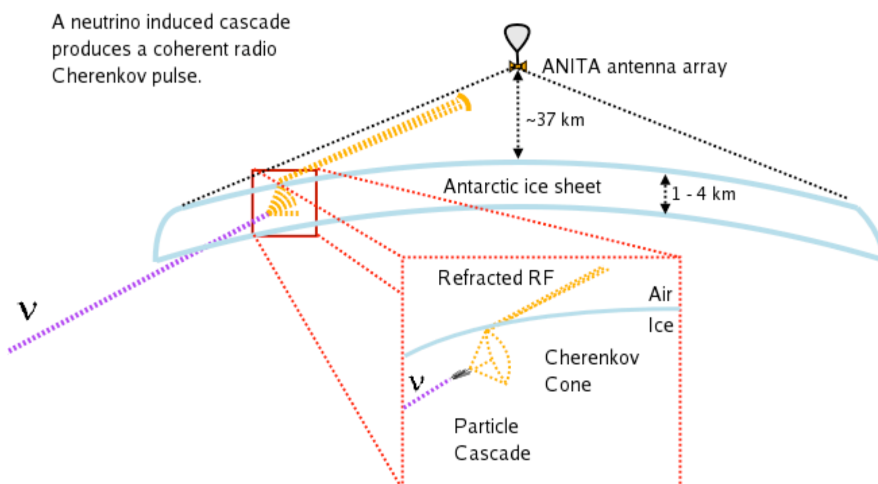

Figure 3. Askaryan effect in the ice. The diagram is made by ANITA collaborator and later found in OSU ASPIRE presentation

Moreover, ANITA experiment adopts a trigger system into the control of its detection since it is mainly looking for neutrinos at energy range of 10^{18} to 10^{21} eV. The signals from the interactions of lower energy neutrinos are more likely to happen as the background radiation than the higher energy ones, and we want to eliminate the response to background signals in our detection. First, a trigger system in particle physics experiment is used to select infrequent events and suppress the background as much as possible, which matches the physic event rate to the data acquisition rate [7]. In our experiment, the signals from UHE neutrinos are the events that we want to select, while other signals from lower energy ($<10^{18}$) become the background that we want to suppress. Since UHE neutrinos are rare to find among all neutrino radiations, the triggering is important to the success of ANITA experiment. With the same reason, the experiment uses Monte Carlo simulation to predict the events coming out from the trigger, which is explained in the later section.

METHOD & TOOLS

The ANITA research team has developed a tool called icemc to simulate the experiment, which models the balloon-payload detector and predicts the number of events passing through the trigger. Since ANITA experiment requires the trigger system to control the energy level of observation, the icemc uses Monte Carlo algorithm that can predict the number of UHE neutrino interactions coming out from all neutrinos generated in the simulation. This package of codes is currently maintained on GitHub Repository (Table 1) and made up of several classes such as primaries, balloon, trigger, and icemodel [6]. We put a group of inputs including neutrino number and energy level into the icemc in order to receive a simulated result of interacted events and their distributions associated with different experiment variables. Comparing the results from various inputs or different versions of icemc helps test the simulation and improve the development of icemc.

To better visualize the results from the simulation, ANITA collaborators at OSU has built a useful tool called icemcQC that can run the simulation program with various inputs and make histogram plots of experiment variables using the simulated data. The later section gives some examples of these plots and explains how they describe the neutrino signals. Since QC stands for the quality and control, icemcQC is then the quality and control of icemc. The purpose of icemcQC is to monitor the simulation of icemc and provide plots showing different runs of icemc for ANITA experiment to compare, which allows the collaborators to easily access the plots instead of having to make them on their own. On the other hand, these analysis plots give good demonstration on the ANITA works, allowing new students to obtain intuition for physics research. It simplifies the steps to make comparison between expectations from different energies and flight numbers. This package of codes is currently stored on GitHub Repository (Table 1).

Members in the QC group maintain the function of icemcQC, make plots from the latest version of icemc, and increase the types of plots. Different from the common understanding of research, major work of QC is focused on programming and system operating of the shells on the supercomputer cluster, such as fixing the programming of icemcQC and writing the scripts for plotting.

IcemcQC codes are executed on the cluster built by Ohio Supercomputer (OSC). Owens is one of the supercomputers which the QC group use most frequently to run icemcQC program. We also need the supercomputer Unity and online server Radiorm built by OSU College of Art & Science for publishing and updating the plots. Following the structure of icemc, we build the bash-shell environment of icemcQC on the cluster and use ROOT to read data files. IcemcQC have several components including the shell files and the plotting scripts. The shell scripts written in computer language Unix carry out the executing work of icemcQC program, while the plotting part of icemcQC is written in computer language C/C++ within ROOT. The latest plots completed by icemcQC are displayed on the website of ANITA collaboration at OSU (Table 1). The first version of shell files was completed by Khalida Hendricks in 2014 with the shell environment on SVN and later revised by Keith McBride with Brian Clark. Kaeli Hughes and Natalie Keyes wrote the initial version of the plotting scripts in C++. In my research, the problems of shell files have been revised and plotting scripts are improved to make the plots that have been demonstrated to the website of ANITA collaboration at OSU.

icemc on GitHub:	https://github.com/anitaNeutrino/icemc
icemcQC on GitHub:	https://github.com/osu-particle-astrophysics/icemcQC_keith
Plot comparison:	http://anita.physics.ohio-state.edu/icemcqc/compare.php

Table 1. Locations of icemc, icemcQC, and analysis plots. The simulation program icemc is completed by ANITA simulation group both at OSU and other collaborators. The quality and control program icemcQC is completed by the QC group at OSU, which was first written by Khalida Hendrick in 2014 and revised by Keith McBride in 2018. It is currently broken due to some programming issues. There is a simplified version (icemcQC_V_N) stored as zip file in the same repository completed by Victoria Niu in 2019. The webpage of plot comparison is initially built by the OSU ANITA group and revised by Brian Clark in 2018. The demonstrated plots of simulated data from icemc are made by Victoria Niu using icemcQC_V_N in Nov 2019.

PROCEDURE

The initial plan for the QC group was simple: write plotting scripts in C++, put the scripts into icemcQC program, and run icemcQC to generate the plots. However, the previous icemcQC code written by Khalida Hendrick using cluster of SVN in 2014 was moved to the cluster of GitHub in 2016 in order to match the work of icemc. The change of shell environment broke some executions of the code and path of the directories so that icemcQC cannot compile and run thoroughly to generate plots. This issue was temporarily fixed by us in summer 2018 but reappeared after an update of icemc. With the complexity of running icemc and new assistance tools developed by the icemc team, structure of previous icemcQC is not able to cope with the various update of icemc and execute the assigned jobs. Broken pipes of icemcQC often exist and need debugging, when icemc is updated. Half of my research time was then spent on learning and debugging the previous icemcQC code on GitHub.

Meanwhile, hardware rearrangement in OSC supercomputers results in multiple jobs running at the same time instead of one large job, which requires a comprehensive program to submit icemc jobs many times to the supercomputer. In other words, the QC group still needs a program that follows the crucial steps of the broken code to generate the simulated data. After consulting Dr. Connolly, we decided to write codes of a simplified icemcQC program that can maintain the basic functions of the previous icemcQC, since our goal is to make analysis plots rather than build a perfect program. I rebuilt the shell environment on the Owens and wrote the code of new QCSubmit and QCPlotter, which now can comprehensively execute the major work of icemcQC. All bash and plotting scripts are assembled into the icemcQC_V_N directory on the GitHub repository of icemcQC as an alternative solution to icemcQC assignments. Table 2 shows the files in icemcQC_V_N and their functions. Figure 2 is the execution flow of the current icemcQC.

Bash shell environment	
bash_profile	written in Linux; export environmental variables for running icemc
bashrc_anita.sh	written in Linux by Brian Clark; set up the shell for icemcQC
Run simulation icemc	
QCSubmit.sh	written in Linux; run icemc at different energy levels and inputs; create output directories to store the simulated root files.
run_icemc.sh	written in Linux; the job submitted by QCSubmit.sh to Owens
Plotting code	
QCPlotter.sh	written in Linux; execute the plotting assignment of icemcQC
M.read_Primaries	written by the previous QC group, complier of read_Primaries.cc
read_Primaries.cc	written in C++; make the analysis plots of primary-branch variables
M.trigger	written by the previous QC group, complier of trigger.cc
trigger.cc	written in C++; make the analysis plots of trigger-branch variables

Table 2. List of the files in icemcQC_V_N and their functions.

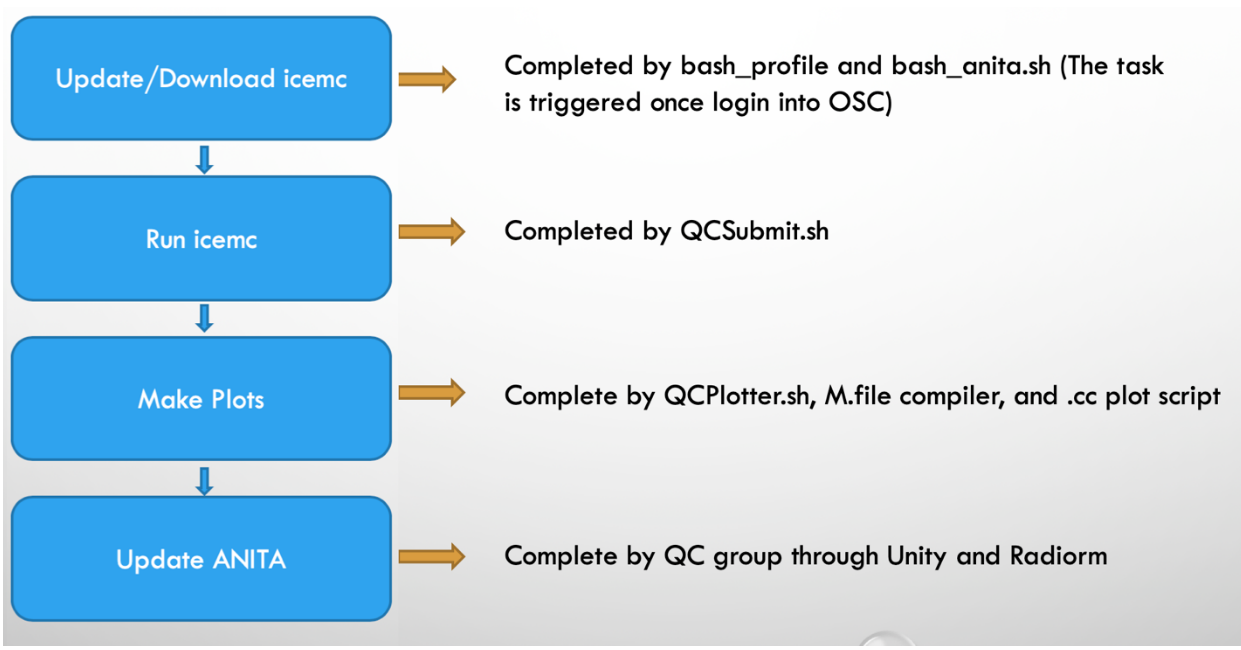

Figure 4. Execution Flow of the current icemcQC (the code of icemcQC_V_N)

The shell environment files, bash_profile and bash_anita.sh, can be stored on the cluster. It should run itself automatically every time QC user login into the Owens, which sets up the shell for running the simulation program and checks the update of icemc. Next, the QC group run QCSubmit.sh using bash or source command with the level of neutrino energy they want to trigger. QCSubmit will locate the run_icemc.sh and submit the jobs to Owens. By default, five jobs of run_icemc.sh will be submitted and 2,000,000 neutrinos are triggered in each job for each run of QCSubmit. QC user can change the setting in QCSubmit to run icemc with different energy levels and neutrino numbers. Although the QC group currently get results from the third ANITA simulation, input files can also be changed in QCSubmit.sh if other simulation versions are attempted. After running icemc jobs are completed on Owens, we execute the QCPlotter.sh by bash or source command with the branch of neutrino variables we want to study. QCPlotter will read the ROOT files of the simulated data and make plots by triggering the plotting script. Both pdf and png files of the analysis plots are stored on Owens, which are later moved to Unity and Radiorm. The ANITA group is able to find these plots and compare two simulation results of different input parameters.

RESULTS & COMPARISON

The icemcQC currently is able to check the update, run the simulation, and make good plots using the simulated data. The type of the plots involves 32 primary variables and 5 trigger variables. These primary variables show the most fundamental properties of the neutrinos that we will observe from ANITA and are crucial to the improvement of the simulation. All these plots are published in the plot-comparison section on the website of ANITA collaboration at OSU, where the ANITA group can view and download them. Figure 5-9 give examples of some plots. Table 3 shows a list of plots made by icemcQC and the physical meanings of each plot.

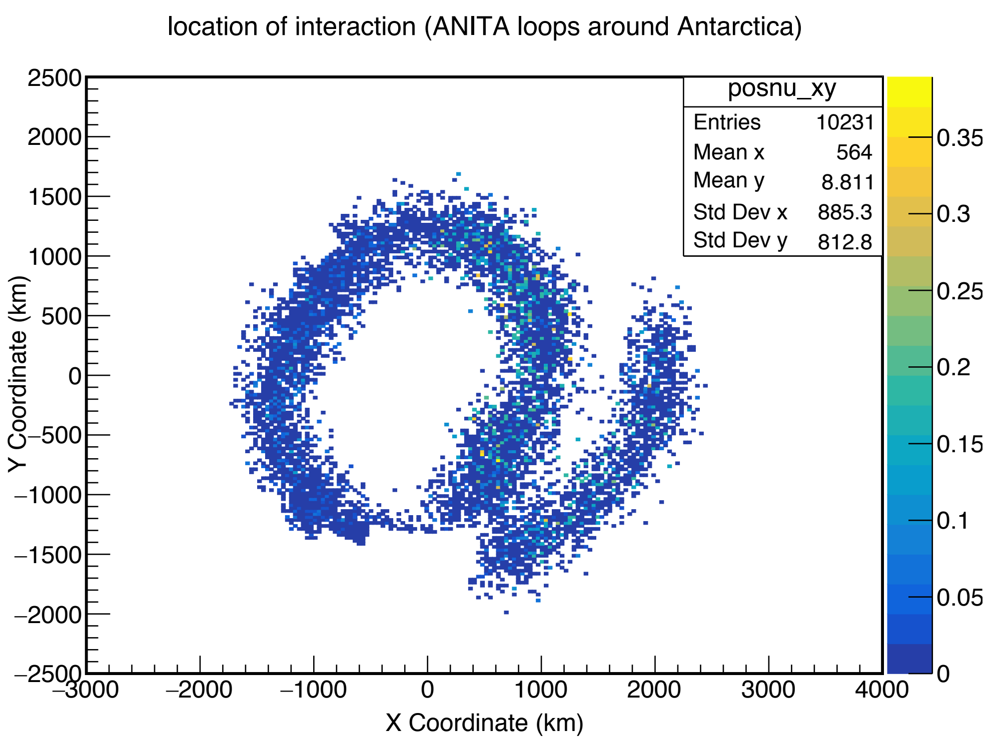

Figure 5. Location of neutrino interaction triggered at energy E=10^{20} eV with neutrino number N=10^7. The plot demonstrates the location of interaction in two dimensions, where the height of the detector is not included. The trajectory shows a closed loop since the balloon detector loops around the Antarctica along the contour of the continent. The color on each data point shows the probability of finding neutrino signal at this location. The statistic box gives the average value of the interacted position on x-axis and y-axis.

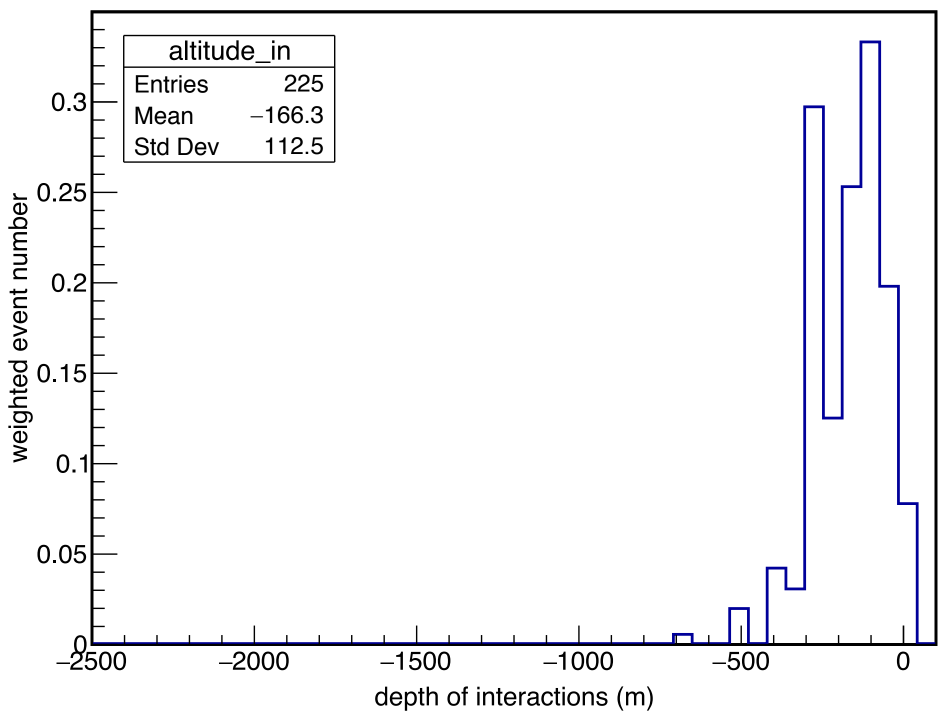

Figure 6. Depth of neutrino interaction triggered at energy E=10^{18} eV with neutrino number N=10^9. The plot shows the distribution of the neutrino altitudes when they interact with the ice. There are only 225 interactions at energy level 10^{18} eV if 10^9 neutrinos are triggered. The average depth of all interactions is around -166.3 m.

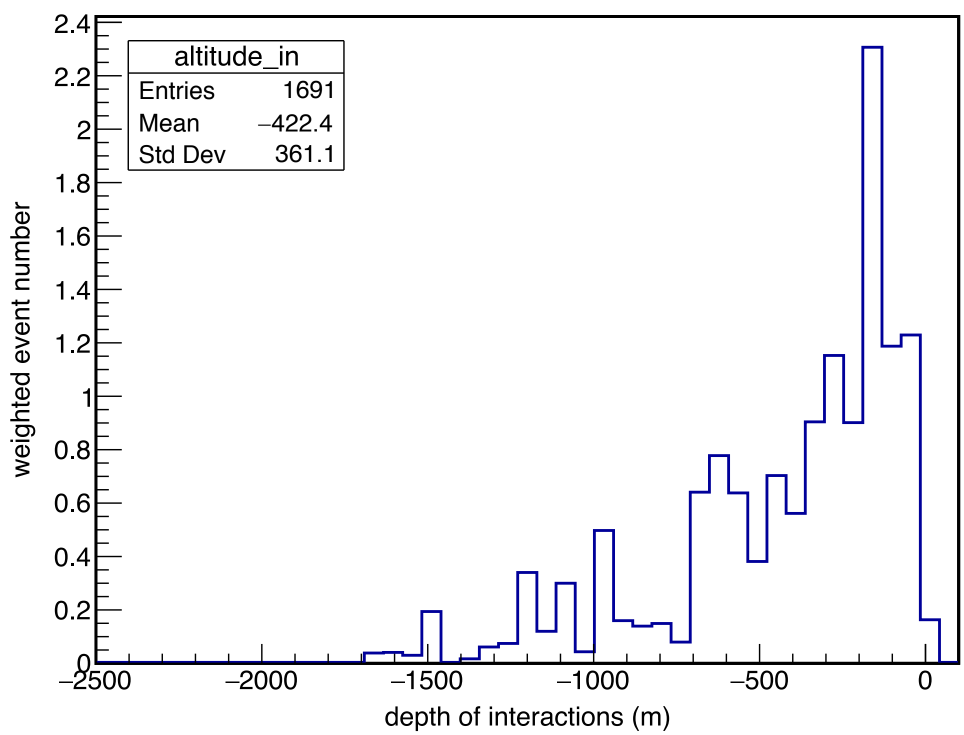

Figure 7. Depth of neutrino interaction triggered at energy E=10^{19} eV with neutrino number N=10^7. The plot shows the distribution of the neutrino altitudes when they interact with the ice. There are 1691 interactions at energy level 10^{19} eV if 10^7 neutrinos are triggered. The average depth of all interactions is around -422.4 m.

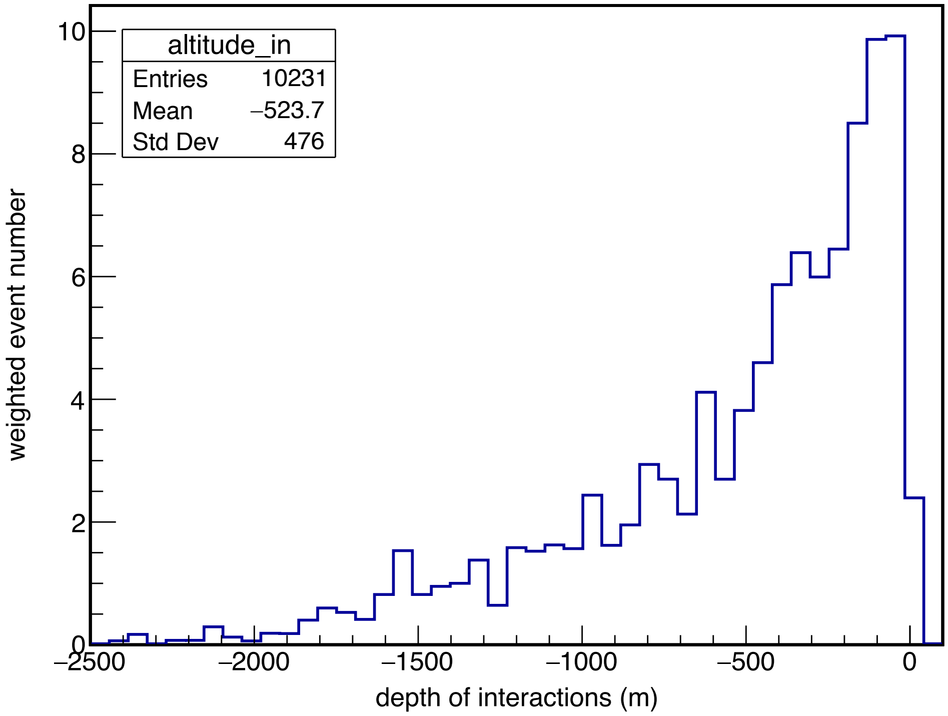

Figure 8. Depth of neutrino interaction triggered at energy E=10^{20} eV with neutrino number N=10^{7}. The plot shows the distribution of the neutrino altitudes when they interact with the ice. There are 10231 interactions at energy level 10^{20} eV if 10^{7} neutrinos are triggered. The average depth of all interactions is around -523.7 m.

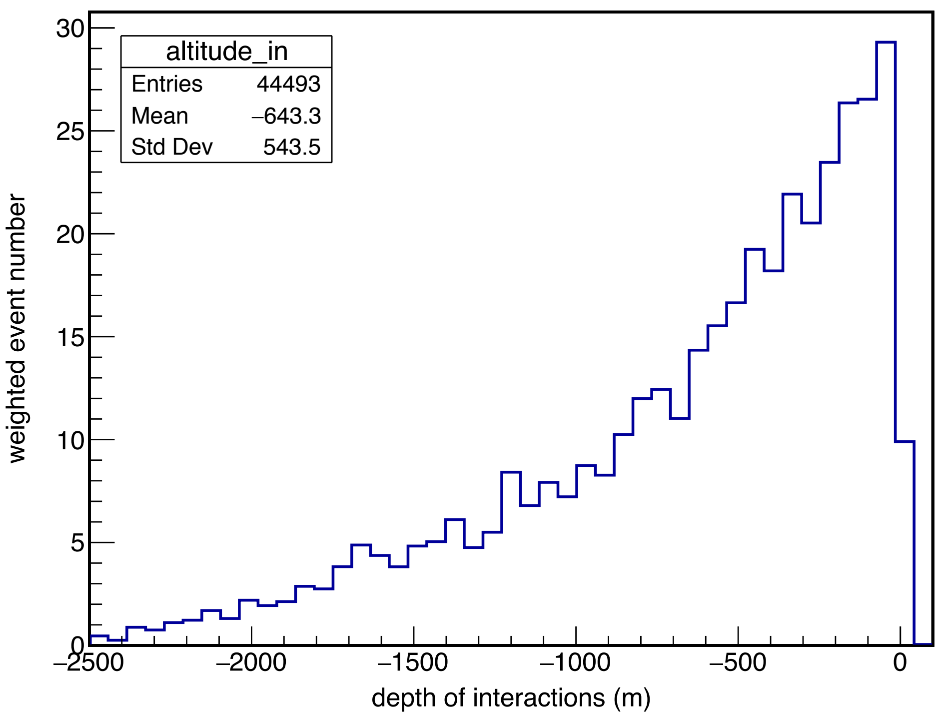

Figure 9. Depth of neutrino interaction triggered at energy E=10^{21} eV with neutrino number N=10^{7}. The plot shows the distribution of the neutrino altitudes when they interact with the ice. There are 44493 interactions at energy level 10^{21} eV if 10^{7} neutrinos are triggered. The average depth of all interactions is around -643.3 m.

Figure 5 simply shows an example of the distribution of neutrino interactions in the ice at energy level 10^{20} eV. The histograms in figure 6-9 demonstrate a varying distribution of the depth of interaction at different energies. Neutrinos are more possible to interact with the ice when entering the ice rather than leaving the ice. However, the signals generated at the entrance of the ice are less likely to be detected by ANITA, since the ice itself absorbs and scatters the photons. In figure 8 and 9, we see more events happening at the deeper location. It shows that the signals of neutrinos with higher energy (10^{20} to 10^{21}) better survives the ice and reach the antennas than those of lower energy (10^{18} to 10^{19}). The plot comparison implies an energy dependency of the neutrinos detected by ANITA.

Plot Name	Description
primary-class variables:	
altitude_in	the depth from the sea level of neutrino interacted with the ice
chord	chord-length from the Earth entrance to the rock-ice boundary
chord_kgm2_bestcase	chord-length that neutrino would traverse if it was crust density
cos(theta)	cosine of the theta angle of neutrino interacting direction from the Earth center to the balloon in spherical coordinate
currentint	the charge of neutrino: 0 is neutral, 1 is charged
d1+d2	distance from the Earth entrance to the interaction point
d1	distance from the Earth entrance to the rock-ice boundary
d2	distance from ice-rock Boundary to the interaction point
dviewangle_deg	deviation from the cerenkov angle
dtryingdirection	weighting factor: the number of equivalent tries that each neutrino counts for after having reduced angular phase space for possibly-detectable events
fresnel1	net fresnel factor on field at ice-firn interface
fresnel2	net fresnel factor on field at firn-ice interface
logchord	log10 of chord-length from the Earth entrance to rock-ice boundary
mybeta	the beta angle minus 90 degree; beta:the angle with respect to the horiztoal where the ray hits the balloon
mytheta	the alpha angle minus 90 degree, alpha: the angle between neutrino momentum and surface nromal at the Earth entrance point
n_exit_phi	phi angle of the ray from the surface to balloon in spherical coordinate
nnucostheta	cosine theta of neutrino direction when interacting in spherical coodinate
nnuphi	phi angle of neutrino direction when interacting in spherical coodinate
nuexit	distance where neutrino would have left the Earth to the Earth center
nuexitice	distance where neutrino would have left the ice to the Earth center
nuflavorint	neutrino flavor (1=electron, 2=muon, 3=tau)
posnu_xy	location of interaction inside the ice in the Cartesian coordinate (projected to x-y direction)
r_enterice	distance to the Earth center where neutrino enters the ice
r_exit2bn	predicted surface distance where neutrino exits the balloon
r_exit2bn_measured	measured surface distance where neutrino exits the balloon
r_fromballoon	surface distance of interaction point
r_fromballoon_sq	surface distance squared of interaction point
r_fromballoon_sq_vs_depth_int	surface distance squared of interaction point v.s. depth of interactions
r_fromballoon_vs_depth_int	surface distance of interaction point v.s. depth of interactions
r_in	distance to the Earth center where neutrino enters the Earth
rin_costheta	cosine theta of neutrino direction when entering the Earth in spherical coordinate
rin_phi	phi angle of neutrino direction when entering the Earth in spherical coordinate
theta	the angle of neutrino interacting direction from the Earth center to the balloon as z-axis
theta_rf_atbn	polar angle of the signal as see by perfect eyes at the balloon
weight_bestcase	the weight of events if whole Earth had density of crust
trigger-class variables:	
trigger	distribution of the neutrino interactions on the trigger number
nchannels_triggered	the number of the channels that are triggered
eventsfound_beforetrigger	the number of events found before entering the trigger
l3trig	antenna number on the third layer trigger
l2trig	antenna number on the second layer trigger
l1trig	antenna number on the first layer trigger

Table 3. The names of plots currently made by icemcQC and the physical meanings of each plot.

FURTHER IMPROVEMENT

A further step of automation should be achieved by the QC group, which checks the update of icemc within a period of time and runs the simulation to make plots if icemc is updated. The automation enables the ANITA collaborator to access the latest simulation results from icemc as soon as possible. The QC group should also start to make plots from the simulations of ANITA 1^{st}, 2^{nd}, and 4^{th} flights (currently doing Anita 3^{rd} flight), which can increase the range of plot comparisons.

ACKNOWLEDGEMENT

Full acknowledgement to Khalida Hendricks for writing the initial icemcQC code. Thanks to Kaeli Hughes, Brian Clark, and Keith McBride for collaboration and development of icemcQC and ANITA plot comparison. Further thanks to CCAPP and 2018 Physics Summer Research program of OSU Department of Physics. The list below is the names of people who have participated in the code writing of icemcQC program:

Khalida Hendricks: original icemcQC codes in icemcQC_keith

Keith McBride: icemcQC_keith

Brian Clark: initially write bash_anita.sh, M.read_Primaries, and read_Primaries.cc

Kaeli Hughes: initially write M.read_Primaries and read_Primaries.cc

Natalie Keyes: initially write trigger.cc

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